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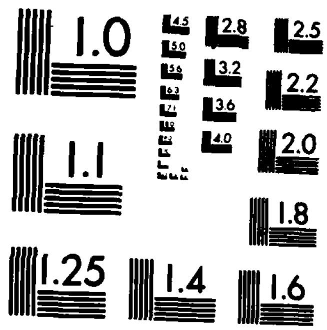
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In-House Report
June 1984

ANALYTIC MODELS FOR RADIATION INDUCED LOSS IN OPTICAL FIBERS II. A PHYSICAL MODEL

James A. Wall

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An analytic expression based on a relatively simple phenomenological physical model for radiation induced losses in optical fibers was derived. The expression yielded excellent fits to RADC data on steady-state induced loss in optical fibers. Using the model, it may be possible to gain insight into the reasons for differences in the radiation responses of nominally similar fibers. This could give clues for procedures to improve the radiation hardness of optical fibers.

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Block 11 (Contd)

Induced Loss in Optical Fibers II. A Physical Model

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Illustrations

Analytic Models for Radiation Induced Loss in Optical Fibers II. A Physical Model

1. INTRODUCTION

In a previous report,[1] we showed that the steady-state radiation induced loss in optical fibers could be described by a simple power law of the form

$$L = AD^n \tag{1}$$

where

L is the induced loss in dB/unit length,

D is the radiation dose absorbed by the fiber, and

A and n are empirical constants.

Although this expression provides good to excellent fits to optical fiber induced loss data, we could not find a reasonable physical model to explain why it could be used to describe the data so well. An expression that could fit induced loss data and be related to a physical model is clearly much more desirable because the constants derived from the data fits could, at least in principle, be related to the physical processes involved in the production of induced loss in the fibers. These results could then be used to explain why some optical fibers are more radiation

(Received for publication 12 July 1984)

1. Wall, J.A. (1984) Analytic Models for Radiation Induced Loss in Optical Fibers I, RADC-TR-84-71.

resistant than others of similar composition and optical properties, and could give clues to improving the radiation hardness of optical fibers. An expression, based on a fairly simple phenomenological physical model, that can fit optical fiber induced loss data very well is discussed in this report.

2. DERIVATION

Assume that an optical fiber is irradiated at a dose rate sufficiently low so that all relatively short-term phenomena such as geminate electron-hole recombination, trapped electron or hole energy level transitions, transitions between traps, etc., establish equilibrium levels that are long-term compared to the total duration of the irradiation. (These conditions apply to the majority of steady-state optical fiber irradiations performed at RADC/ES as evidenced by the lack of recovery of induced loss within hours after irradiation.) During the irradiation, the fiber transmission is monitored by a photodiode at the output end of the fiber which detects the amplitude of the light received from a relatively narrow band light-source, such as a light emitting diode or laser diode, coupled to the input end of the fiber. Under these conditions, even though more than one radiation induced absorption band may develop in the fiber, we observe changes in transmission only over a narrow band of wavelengths and we can consider the measurement as the equivalent of the observation of the growth of a single absorption center.

The radiation induced loss in the optical fiber is the result of electrons and/or holes generated by the radiation being trapped by defects or "traps" in the fibers. Not all traps become optical absorbers when occupied by an electron or hole (in fact, the majority probably are not optical absorbers), but, since we observe only optical absorption, we count only those traps that do become optical absorption centers when occupied. Also, we count only those traps that produce absorption (not necessarily their maximum absorption) within the wavelength band of the measurement.

Considering these experimental conditions and definitions, the derivation of the expression for the growth of induced loss in an optical fiber is as follows:

Let N_o = the number/unit volume of intrinsic traps in the fiber,

n_g = the number/unit volume of electron-hole pairs generated by the radiation, and

N_r = the number of traps/unit volume produced by the radiation (such as broken bonds).

Assume $n_g = \alpha D$

$N_r = \beta D$

where D is the dose and α and β are constants.

The differential increase in the number of trapped electrons and/or holes (absorption centers) is proportional to the total number (per unit volume) of available traps and the differential increase in the number of electron-hole pairs generated. (An occupied trap is not available.)

$$dn_t = kdn_g\,(N_o + N_r - n_t) = \alpha k\,(N_o + \beta D - n_t)\,dD \tag{2}$$

where

n_t = number/unit volume of trapped electrons and/or holes, and

k = proportionality constant (this could also be called the probability of occupation), and we have used $dn_g = \alpha dD$.

Dividing Eq. (2) by the differential increase in dose,

$$\frac{dn_t}{dD} = \alpha k N_o + \alpha k \beta D - \alpha k n_t$$

$$\frac{dn_t}{dD} + \alpha k n_t = \alpha k N_o + \alpha k \beta D \tag{3}$$

Eq. (3) has the form

$$\frac{dy}{dx} + ay = b + cx;\ a,\ b,\ c = \text{constants}, \tag{4}$$

the solution of which is

$$y = Ke^{-ax} + \frac{c}{a}x + \frac{ba - c}{a^2}.$$

Using the condition $y = n_t = 0$ when $x = D = 0$, the final solution of Eq. (4) is

$$y = \left(\frac{ba - c}{a^2}\right)\left(1 - e^{-ax}\right) + \frac{c}{a}x.$$

Substituting for a, b, c from Eq. (3), we obtain

$$n_t = \left(N_o - \frac{\beta}{\alpha k}\right)\left(1 - e^{-\alpha k D}\right) + \beta D. \tag{5}$$

The radiation induced absorption coefficient, and therefore the induced loss in

dB/unit length, for the fiber is proportional to n_t. Since we do not know the proportionality factor (which is related to the oscillator strengths of the trapped electrons and/or holes) nor the values of α, β, and k, Eq. (5) is more conveniently written

$$L = A\,(1-e^{-BD}) + CD \tag{6}$$

where

L = induced loss in dB/unit length, and

A, B, and C are constants to be determined empirically.

Although derived independently, the result obtained here is equivalent to the result derived by Levy[2] several years ago regarding radiation-induced color centers in glasses and other nonmetals. However, in his derivation, Levy did not assume the equilibrium irradiation conditions that we have. Also, he did not limit trapping and recombination processes only to those actually observable at the measurement wavelength(s). Consequently, his far more general considerations resulted in a much more complicated expression that is virtually unrecognizable in respect to the result obtained here. In subsequent applications of his model to experimental data,[3,4,5,6] Levy and coworkers found that many of the factors considered in the original model could be neglected, and reduced the more complicated expression to the equivalent of our Eqs. (5) and (6). In fact, their Eq. (2.2)[3] is identical to our Eq. (5) except for notation.

3. DATA FITTING PROCEDURE

Eq. (6) cannot be linearized. Thus, in attempting to fit this expression to optical fiber radiation induced loss data, we are dealing with nonlinear regression,

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2. Levy, P.W. (1960) The kinetics of gamma-ray induced coloring of glass, J. Am. Ceram. Soc. 43:389.

3. Levy, P.W. (1961) Color centers and radiation-induced defects in Al_2O_3, Phys. Rev. 123:1226.

4. Lengweiller, K., Mattern, P.L., and Levy, P.W. (1971) Studies on nonmetals during irradiation: The growth of F centers in KCl at 85°K, Phys. Rev. Letters 26:1375.

5. Levy, P.W., Mattern, P.L., Lengweiller, K., and Bishay, A.M. (1974) Studies of nonmetals during irradiation: V. Growth and decay of color centers in barium aluminoborate glasses containing cerium, J. Am. Ceram. Soc. 57:176.

6. Mattern, P.L., Lengweiller, K., and Levy, P.W. (1975) Effects of ^{60}Co gamma-ray irradiation on the optical properties of natural and synthetic quartz from 85 to 300 K, Radiation Effects 26:237.

an area that involves at least as much ingenuity as it does statistical routine. A detailed description of the fitting procedures is not appropriate for this report; therefore, only an outline of the methods for obtaining values for the constants A, B, and C will be given.

If there is sufficient data of reasonably high precision at both high and low doses, approximate values of the constants can be obtained using the limiting approximation for the exponential term.

For large values of D,

$$(1 - e^{-BD}) \approx 1. \tag{7}$$

Substituting Eq. (7) into Eq. (6) gives

$$L \approx A + CD. \tag{8}$$

Thus, a linear fit to the data for large values of D yields approximate values of A and C provided the product BD is sufficiently large.

For small values of D,

$$(1 - e^{-BD}) \approx BD, \tag{9}$$

and

$$L \approx (AB + C)\,D. \tag{10}$$

The slope of the line obtained from a linear fit to the data at low doses thus gives an approximate value of (AB + C) that, combined with the values of A and C obtained from the fit to Eq. (8), yields an estimate of B.

Clearly, the validity of the above procedure depends on the judgement of the person performing the calculations regarding the range of D to be used and the sufficiency as well as the precision of the data. Under the proper conditions, some very good data fits can be obtained by this method.

Another procedure that can be used to estimate A, B, and C is to use finite difference methods to approximate the second derivative of Eq. (6). The true second derivative is

$$\ddot{L} = - AB^2 e^{-BD}. \tag{11}$$

An exponential fit to the negative of the approximate second derivative of the

data therefore gives estimated values for A and B. Using only the value for B (since A is derived from the product AB^2 and may be subject to greater error) and rewriting Eq. (6) as

$$\frac{L}{D} = A \left(\frac{1 - e^{-BD}}{D} \right) + C, \tag{12}$$

a linear fit of L/D vs $(1 - e^{-BD})/D$ gives values for A and C. In principle, this method should give better estimates of the constants than those obtained by fitting Eqs. (8) and (10). Unfortunately, even the best of real data seldom lives up to our expectations, and numerous sign reversals may occur in the approximation of the second derivative of L. Again, it is up to the individual to decide which portion of the data to keep or discard when sign reversals occur, or to decide whether or not the procedure is usable.

The procedure actually used in fitting the RADC data on optical fiber induced loss to Eq. (6) was the Gauss-Newton or "Taylor expansion linearization" method. This method, which may also be found under other names, is described in more advanced texts on regression[7] or numerical data analysis and will not be explained here. It is an iterative method that requires as a starting point estimates of the constants involved in the expression to be fit. In the present case, initial estimates of A, B, and C may be obtained by the procedures described above or by "guesses" based on data plots or any other method the individual may choose. Poor initial estimates of the constants (among other things) can cause lack of convergence or "blow-up" of the iterative procedure.

Computer programs for data fitting that use this method or modifications of this method are available. However, since only three constants are required to fit Eq. (6), it was decided to develop a program for the method on a Texas Instruments TI-59 programmable calculator. Using the TI-59 permits evaluation of each stage of the iteration process so that corrective action can be taken in case convergence does not appear to be occurring. (Convergence means that the sequential differences between the calculated values of each constant approaches zero as the iterations proceed.) This also has the advantage of eliminating the wait for computer time. An additional report is planned to cover this data fitting method and the calculator program developed to implement it.

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7. Wonnacott, A.J., and Wonnacott, T.H. (1981) Regression, John Wiley & Sons, New York.

4. RESULTS

Eq. (6) was fit to radiation induced loss data for the same varied group of 25 optical fibers for which fits to Eq. (1) were reported.[1] All of the fits were excellent. Figure 1 shows examples of the quality of the fits, one for a relatively radiation-sensitive fiber and one for a relatively radiation-hard fiber. The curves calculated from the fits to Eq. (6) are essentially in exact coincidence with the data. The two fibers for which data is shown in Figure 1 are the same fibers used as examples of "good" fits to Eq. (1) in a previous report.[1] In that case, the fit for the more radiation-sensitive fiber overestimated the induced loss at the higher doses, and the fit for the less radiation-sensitive fiber underestimated the induced loss at higher doses. Clearly, Eq. (6) yields a much better representation of induced loss than Eq. (1).

As a quantitative measure of the quality of the fits of Eq. (6) to the data, the root-mean-square (rms) values of the deviations of the calculated induced losses

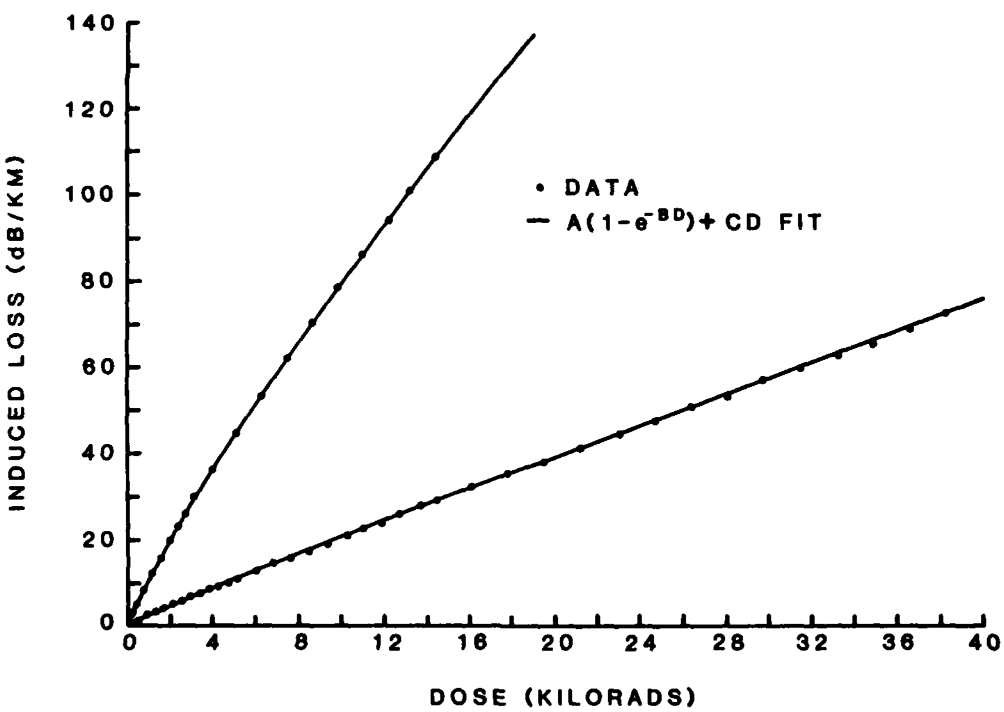

Figure 1. Examples of Fits of Eq. (6) to Optical Fiber Radiation Induced Loss Data

from the measured induced losses were computed. The average rms deviation for all of the fibers was 0.29 dB/km with a standard deviation of 0.12 dB/km. This is small compared to the estimated 2 dB/km accuracy of the data and is almost a factor of 3 better than the average rms deviation calculated for the fits to Eq. (1).

The 25 fibers for which data fits were made could be broken into two groups, those with boron-doped and those with phosphorous-doped germanium-silicate cores.[1] Since the fibers with phosphorous-doped cores were, on average, more than three times more radiation sensitive than those with boron-doped cores, it is interesting to compare the values of the constants in Eq. (6) obtained from the fits to the data for the two groups. For the fibers with boron-doped cores, the average values and standard deviations were: A, 9.17 ± 3.9; B, 0.212 ± 0.089; and C, 2.16 ± 0.80. For the phosphorous-doped-core fibers, the corresponding values were: A, 9.68 ± 5.18; B, 0.279 ± 0.054; and C, 6.36 ± 0.36. Little difference exists between the constants obtained for the two groups except for C, which would appear to account for the factor of 3 difference in radiation sensitivities between the two groups. Comparing Eqs. (2), (5), and (6), we see that C is related to the number/unit volume of radiation induced traps. This might seem to suggest that the higher average value of C obtained for the phosphorous-doped fibers means that they are more prone to the development of radiation induced traps than are the boron-doped fibers. However, we do not know the value of the factor required to multiply Eq. (5) to convert n_t to units of induced loss, and this factor may well be significantly different for the two types of fiber.

Although our attempts to obtain an analytic expression based on a physical model to describe optical fiber radiation induced loss data have been successful, more information is evidently needed before we can use this model to gain a better understanding of the factors that affect the radiation hardness of optical fibers. The model can be used, however, to help determine what specific additional information is needed. From the above, for example, it is evident that data on the specific absorptivity of the variety of radiation induced absorption centers that occur in doped silicate glasses is essential.

5. DISCUSSION

Even though specific information on the absorptivity of the radiation induced absorption centers in optical fibers is not available, Eq. (5) or Eq. (6) may still be useful in interpreting radiation induced loss data. This would be true, for example, for data on fibers for which it is known, or can reasonably be assumed, that the induced absorption centers are equivalent in absorptivity for the fibers being compared. However, when using the equations for the interpretation of data, it is im-

portant to ascertain that the equilibrium conditions specified in the derivation of the equations existed during the irradiations. This is because the functional form of the equations is not unique to the specific conditions of the derivation.

Radiation induced absorption (loss) data that follows th "saturating exponential" form of Eq. (6) have frequently been interpreted[4,8] as indicating the presence of recovery of the induced absorption or loss during irradiation. This interpretation is not necessarily incorrect. If one assumes a relatively simple form of recovery as a function of time, such as an exponential recovery, it can easily be shown that this adds another term of the form n_t multiplied by a constant (for constant dose-rate) to Eq. (2). The resultant form of the differential Eq. (4) is unchanged, and therefore the solution has the same form as Eq. (6). The constants in Eq. (5), however, will be different, and interpretation of the data in terms of this equation becomes invalid. Even for the assumed simple exponential recovery (which is seldom the observed situation), the exponential multiplier in Eq. (5) takes a form that could not be resolved into individual factors without prior knowledge of the recovery function or considerable additional experimental data.

This caution in the use of Eqs. (5) and (6) for interpreting radiation induced loss data for optical fibers also applies to the performance of the experimental irradiations. Although, for a fiber for which the radiation behavior is unknown, the appropriate dose-rate required to establish the equilibrium conditions cannot be determined a priori, it appears best to perform the irradiations at the lowest available and practical (in terms of irradiation time) dose-rate if a reasonable physical interpretation of the data in terms of the model presented here, or in terms of any other viable model, is desired. Although in principle it may be possible to obtain physical insight into the mechanisms involved in radiation induced losses in optical fibers irradiated under non-equilibrium conditions by the application of more complicated models, the dynamics of the electron-hole pair generation and trapping processes involved can be sufficiently complex to make an analysis of the data intractable, and attempts at interpretation could lead to significantly erroneous conclusions.

These factors should also be kept in mind when evaluating published data on radiation induced losses in optical fibers. A large amount of such data is presented as steady-state induced loss data for which the irradiations were performed at dose-rates considerably higher than necessary to maintain dynamic equilibrium. The lack of equilibrium is usually indicated by significant recovery of the induced loss immediately following cessation of the irradiation, although post "steady-state"

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8. Friebele, E.J., Schultz, P.C., and Gingerich, M.E. (1980) Compositional effects on the radiation response of Ge-doped silica-core optical fiber waveguides, Appl. Opt. 19:2910.

irradiation recovery data is not always presented in the publications. Caution and judgment must be exercised in comparing the results reported for fibers irradiated under such conditions. In general, it is best to assume that the results apply only to the specific conditions of the irradiations and that extrapolations to different conditions may be completely meaningless.

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